ECE 371
Materials and Devices

09/19/19 - Lecture 9

Drift Current, Effective Mass, Holes

General Information

- Homework #3 assigned, due Tuesday 10/1
- Homework #2 solutions posted
- First midterm (covers Ch. 1 and Ch. 2) is on Tuesday 9/24
- Midterm will be closed book/notes and consist of:
  - 5-10 multiple choice questions on Ch. 1 and Ch. 2 material
  - 1 question on crystal planes/lattices
  - 2 questions on quantum mechanics
  - Some relevant equations and constants will be provided
  - Calculators okay
- **Midterm review session: Friday 9/19, 11 am – 1 pm, CHTM room 103 (see next slide)**
- Previous midterm questions are posted on the course website on UNM Learn.
- Reading for next time: 3.4, 3.5

CHTM Map

- Review Time and Location: Friday 11 am – 1 pm, CHTM room 103
- Park in lot by building 334 or on the street. DO NOT park directly in front of CHTM. Obtain parking permit from room 103.

Kronig-Penney Model

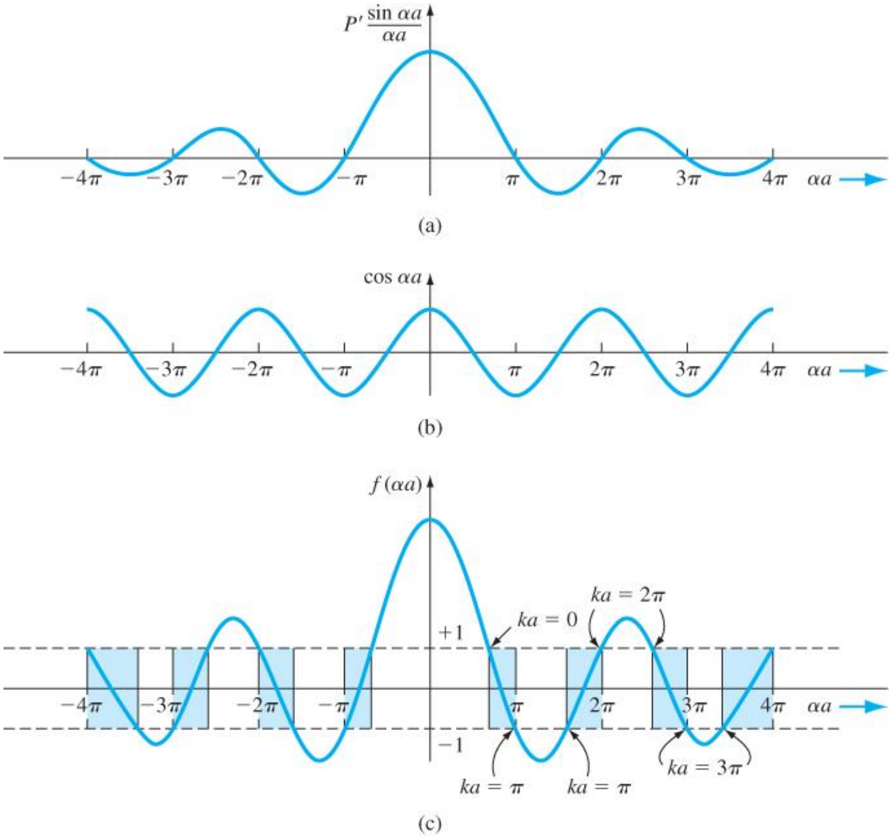


Figure 3.8 | A plot of (a) the first term in Equation (3.29), (b) the second term in Equation (3.29), and (c) the entire $f(\alpha a)$ function. The shaded areas show the allowed values of (αa) corresponding to real values of k.

$$\boxed{P' \frac{\sin(\alpha a)}{\alpha a} + \cos(\alpha a) = \cos(ka)}$$

$$\boxed{P' = \frac{m V_0 b a}{\hbar^2}}$$

- Region where there is a solution to Schrodinger's equation give allowed bands of energies
- If V_0 increases, forbidden bands increase
- As the parameter "a" decreases, the band gap increases

*see in-class derivation

Energy Bands

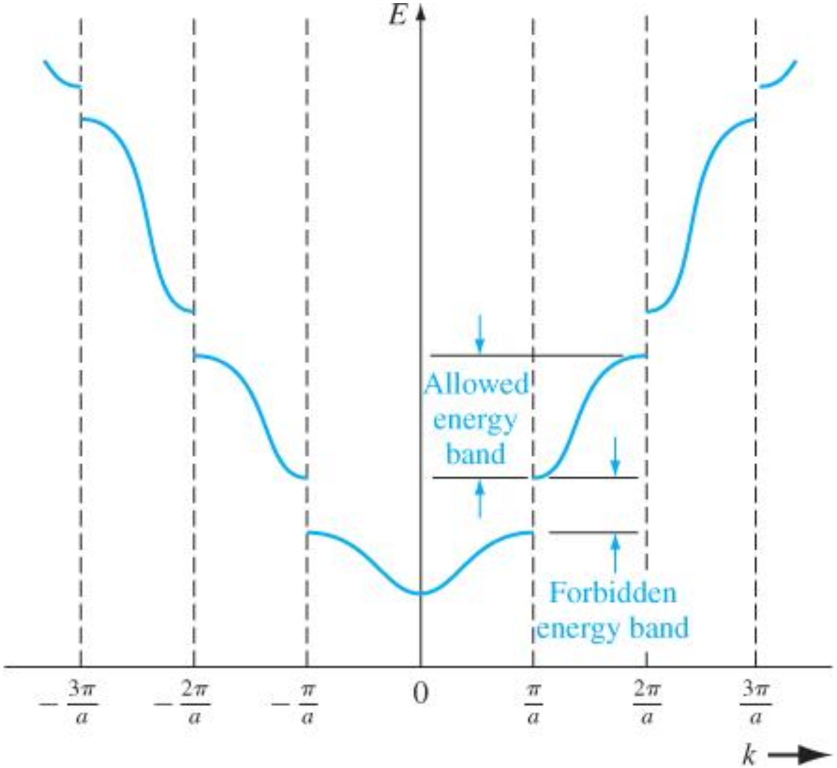


Figure 3.9 | The E versus k diagram generated from Figure 3.8. The allowed energy bands and forbidden energy bandgaps are indicated.

- Kronig-Penney yields concept of allowed and forbidden energies
- Plot E vs. k to reveal the energy bands
- $-\frac{\pi}{a}$ to $\frac{\pi}{a}$ is called the "1st Brillouin zone"

Energy Band Folding

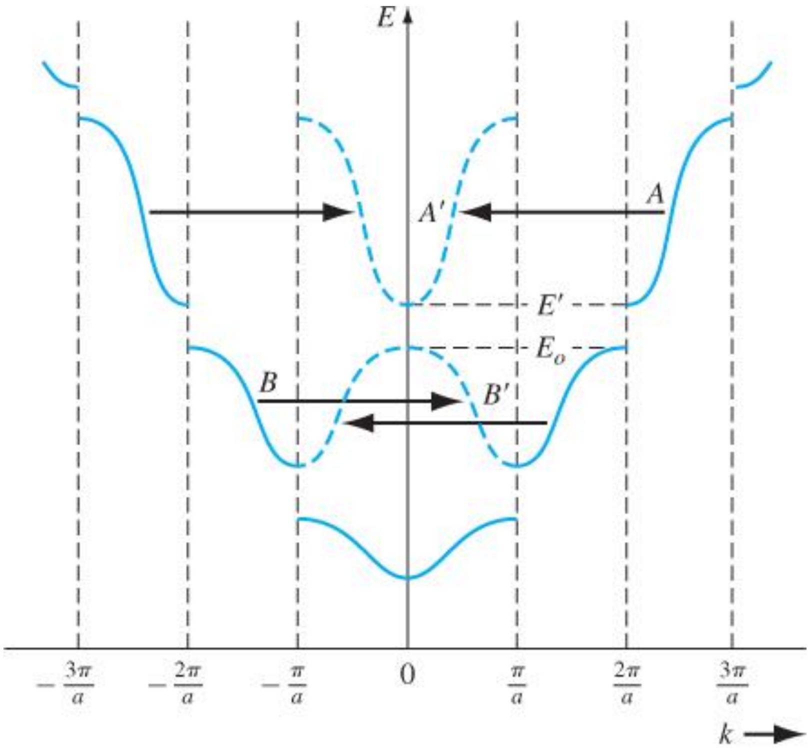


Figure 3.10 | The E versus k diagram showing 2π displacements of several sections of allowed energy bands.

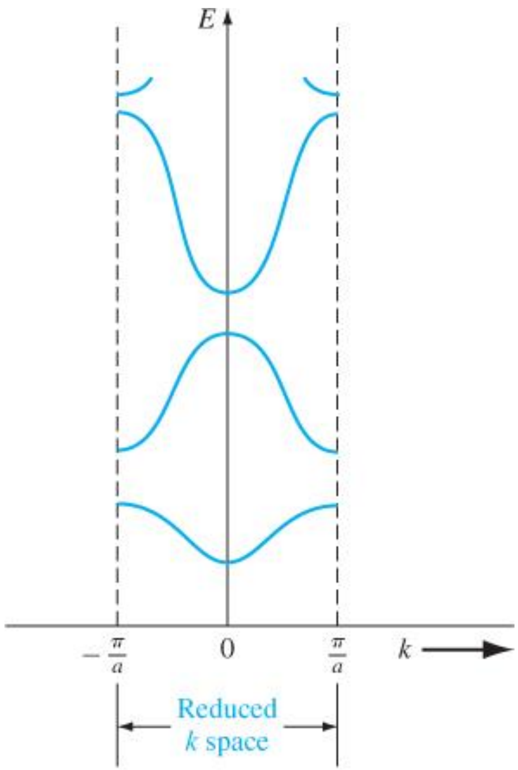


Figure 3.11 | The E versus k diagram in the reduced-zone representation.

Semiconductor Band Structure

- 3-D: dispersion relation depends on propagation direction since the atomic structure and hence the periodic potential depend on the electron propagation direction

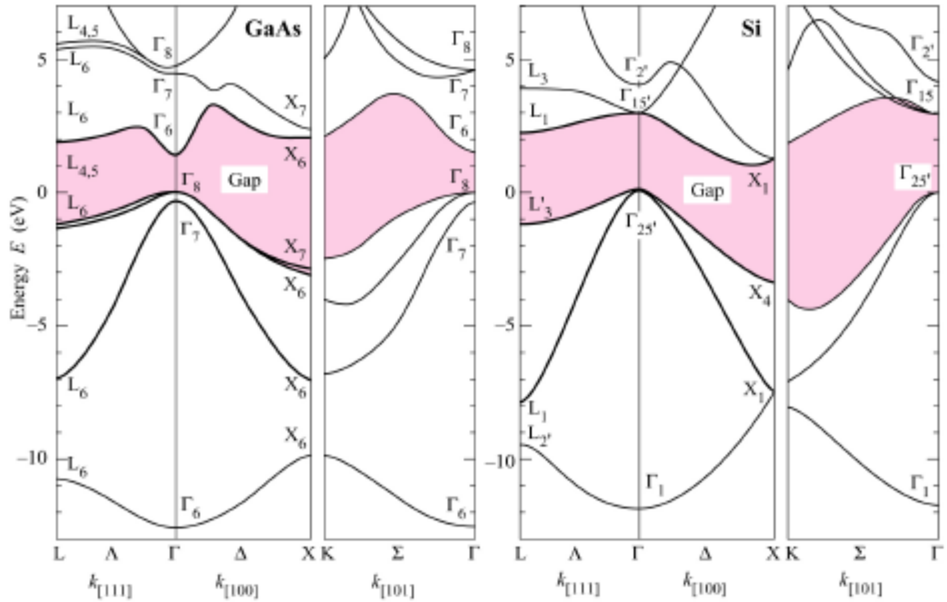
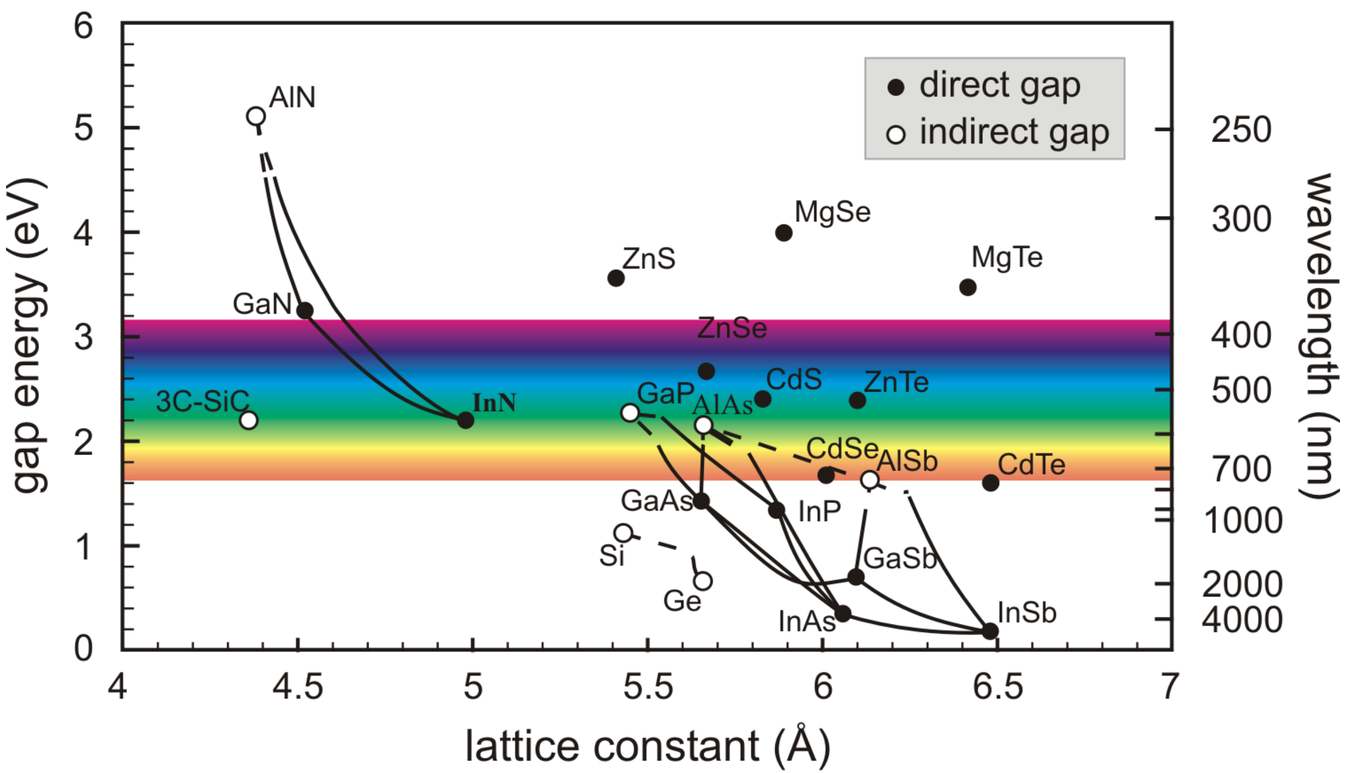


Fig. 8.6 Dispersion relation (band structure) for electrons and holes in the conduction and valence band within the first Brillouin zone for GaAs and Si.

Energy Gap vs. Lattice Constant

- In general, as bond length gets smaller the energy gap increases



Energy Bands and Bond Model

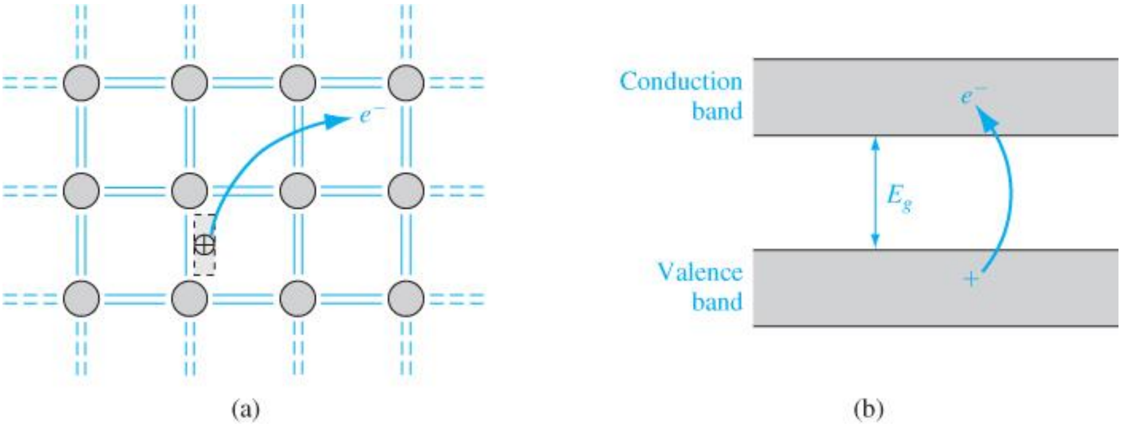


Figure 3.13 | (a) Two-dimensional representation of the breaking of a covalent bond. (b) Corresponding line representation of the energy band and the generation of a negative and positive charge with the breaking of a covalent bond.

- At T = 0 K, all electrons in the valence band
- At T > 0 K, electrons have thermal energy and some covalent bonds may be broken
- Electrons can jump to higher energy levels
- Positive empty states (holes) are left behind in the valence band

Energy Bands and Bond Model

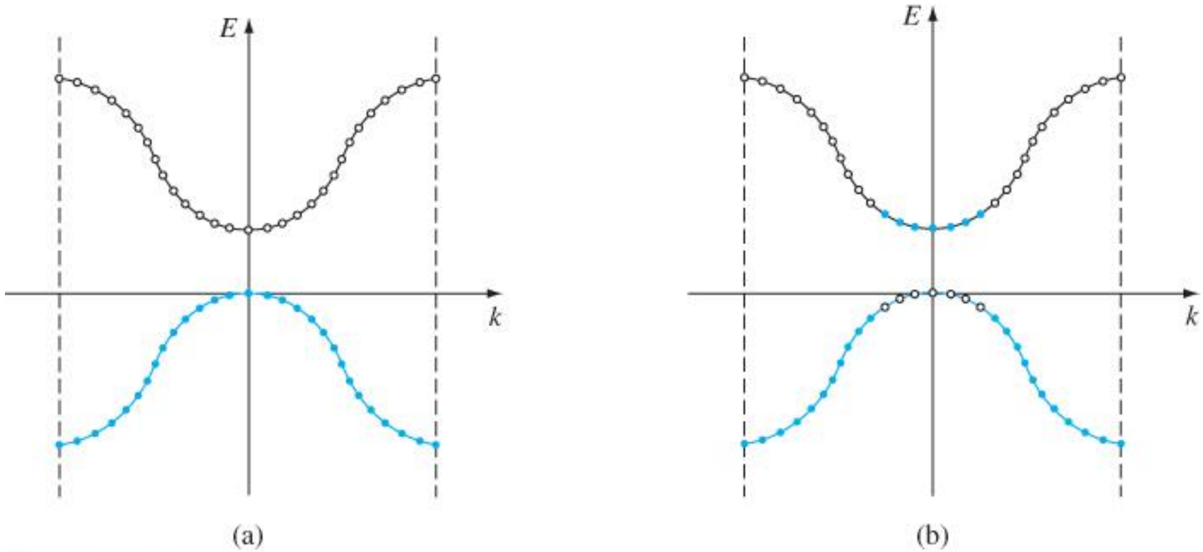


Figure 3.14 | The E versus k diagram of the conduction and valence bands of a semiconductor at (a) $T = 0$ K and (b) $T > 0$ K.

- When all states are filled in a band, no current can flow
- Electrons must be elevated to empty states for current to flow

Drift Current

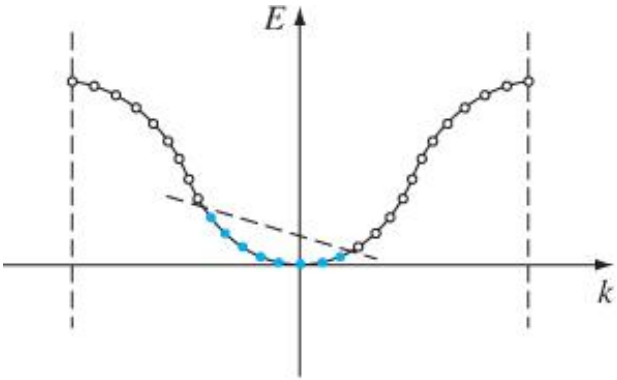


Figure 3.15 | The asymmetric distribution of electrons in the E versus k diagram when an external force is applied.

- Current = net flow of charge
- With an external force applied, electrons in the conduction band can gain energy since there are empty states available

Drift Current:

$$\boxed{J = -e\sum_{i=1}^{n} v_i}$$

- Units for J are A/cm^2
- n = # of electrons per unit volume in the conduction band
- v_i = velocity of a particular electron

Effective Mass Concept

- Movement of an electron in a crystal lattice is different from that in free space
  - Influence of positively charged ions
  - Influence of other electrons

$$\boxed{F_{total} = F_{ext} + F_{int}}$$

- Since we don't know F_{int} very well, we fold it into an "effective mass" (m*)
- Effective mass is given in units of m_0
- Can be higher or lower than m_0
- Can be negative! (hole)
- Allows us to treat electrons in a crystal as classical particles using Newtonian mechanics
- Effective mass influences measurable device properties (current transport in transistors, efficiency of LEDs and solar cells)

The Parabolic Approximation

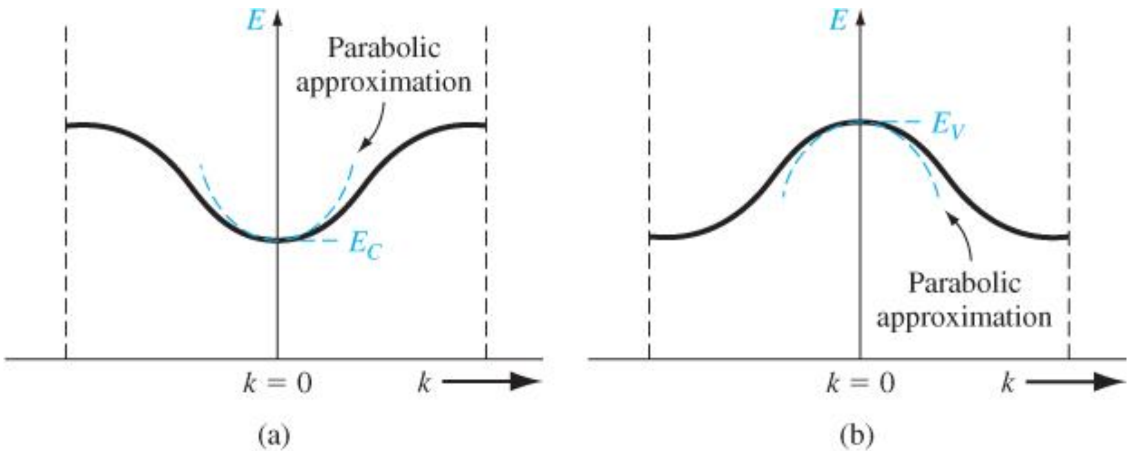
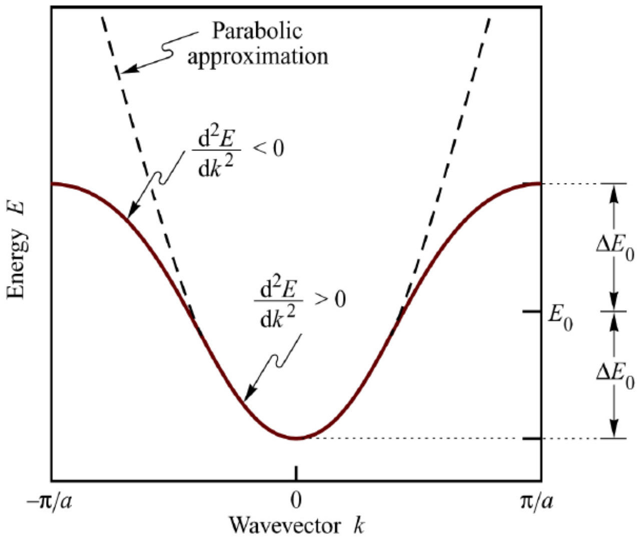


Figure 3.16 | (a) The conduction band in reduced k space, and the parabolic approximation. (b) The valence band in reduced k space, and the parabolic approximation.

- A free electron has a parabolic dispersion curve (E vs. k)
- The dispersion curves for electrons in crystals are roughly parabolic near the bottom (top) of the conduction (valence) bands

Effective Mass



m* depends upon the curvature of the E vs. k curve

$$m^* = \frac{\hbar^2}{d^2E/dk^2}$$

Material	m_n^*/m_0	m_p^*/m_0 (HH)
Si	0.98	0.49
GaAs	0.067	0.45
GaN	0.2	1.2

- Holes typically have larger effective masses than electrons
- Effective mass can be considered roughly a constant near the zone boundaries (e.g., bottom of conduction band)
- In reality, m* depends upon energy (k) and crystal direction
- There are several different effective masses in the valence band (heavy hole (HH), light hole (LH), split-off (SO))

Concept of Hole Motion

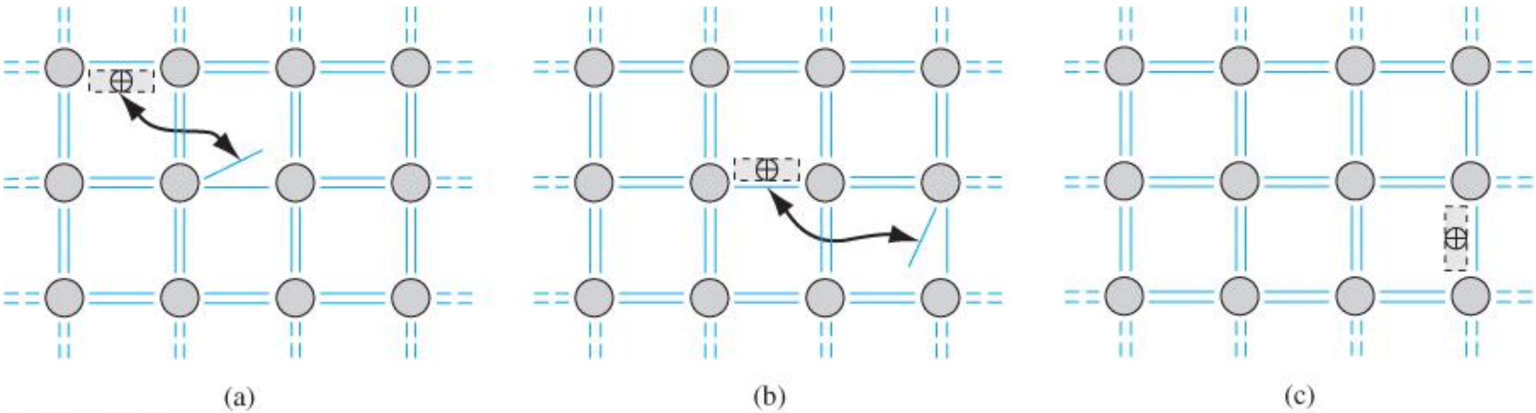


Figure 3.17 | Visualization of the movement of a hole in a semiconductor.

- Movement of electrons to positively charged empty states
- Equivalent to positively charged state moving
- "Holes" give rise to current

Concept of Hole Motion

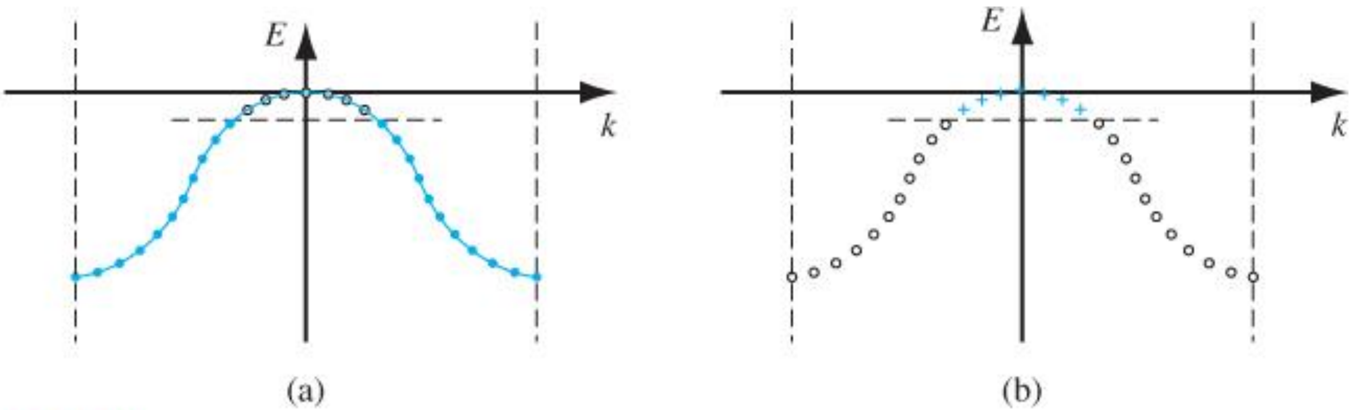


Figure 3.18 | (a) Valence band with conventional electron-filled states and empty states.
(b) Concept of positive charges occupying the original empty states.

Empty electron states → Positive charges occupying empty states

*see in-class derivation

Insulators and Semiconductors

Insulator

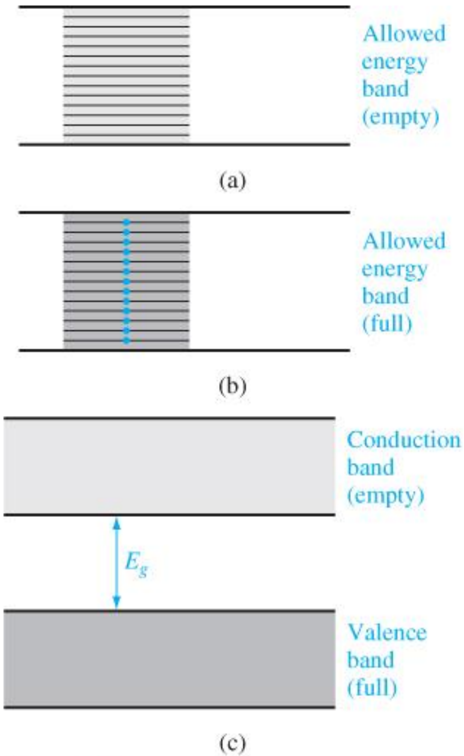


Figure 3.19 | Allowed energy bands showing (a) an empty band, (b) a completely full band, and (c) the bandgap energy between the two allowed bands.

Semiconductor

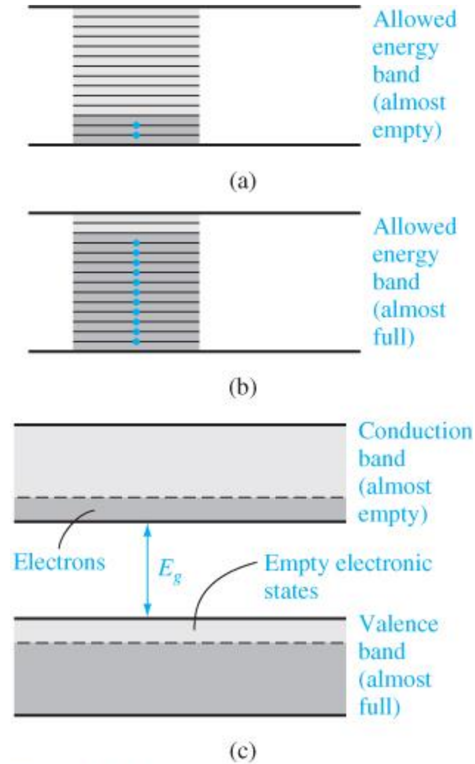


Figure 3.20 | Allowed energy bands showing (a) an almost empty band, (b) an almost full band, and (c) the bandgap energy between the two allowed bands.

Metals

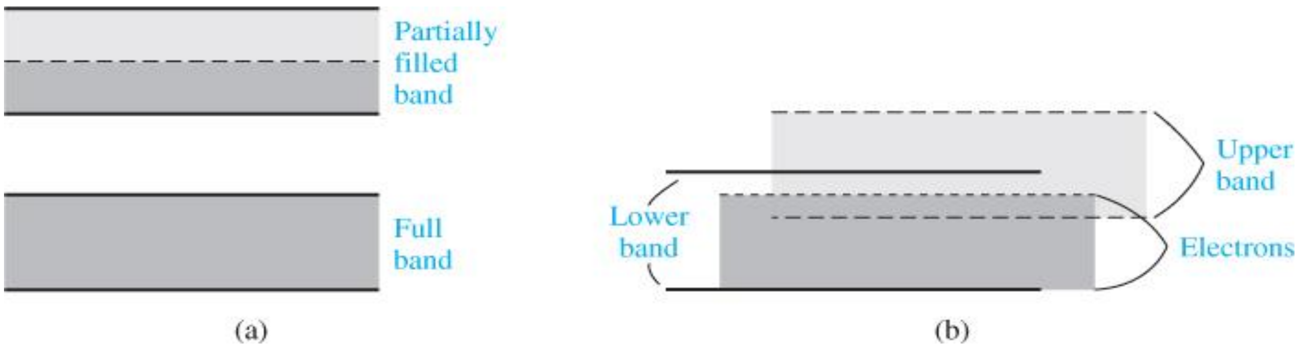


Figure 3.21 | Two possible energy bands of a metal showing (a) a partially filled band and (b) overlapping allowed energy bands.

Test Your Understanding

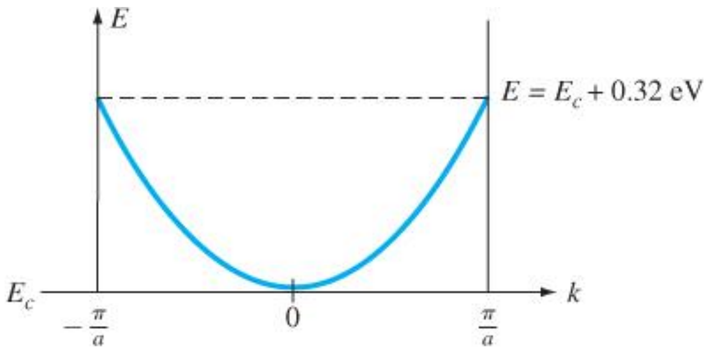


Figure 3.22 | Figure for Exercise TYU 3.3.

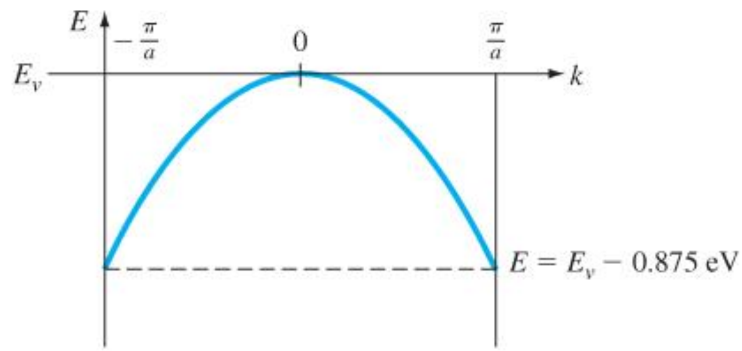


Figure 3.23 | Figure for Exercise TYU 3.4.

TYU 3.3 A simplified E versus k curve for an electron in the conduction band is given. The value of a is 10 Å. Determine the relative effective mass m^*/m_0.
(Ans. $m^*/m_0 = 1.175$)

TYU 3.4 A simplified E versus k curve for a hole in the valence band is given. Assume a value of $a = 12$ Å. Determine the relative effective mass $|m^*/m_0|$.
(Ans. $|m^*/m_0| = 0.2985$)